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(2)

30 April 1992

Office of Navy Research
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Contract No. N00014-91-C-0124
Item No. 0002, Sequence No. A001
800 N. Quincy Street
Arlington, Va 22217-5000

Subject: Submittal of the Progress Report, FR21998-6

Gentlemen:

In accordance with the applicable requirements of the contract, we herewith submit one (1) copy of the subject report.

Very truly yours,

UNITED TECHNOLOGIES CORPORATION
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Margaret B Hall

Margaret B. Hall
Contract Data Coordinator

cc: With Enclosures

Director, Naval Research, Code 2627
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Dr. K. Sadananda

FR2198-06 15 April 1992

FATIGUE IN SINGLE CRYSTAL NICKEL SUPERALLOYS
Technical Progress Report

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15 April, 1992

Period of performance
16 March 1992 through 15 April 1992

Contract N00014-91-C-0124

Prepared for:
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Code 1222

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I. Introduction and Program Objective

This program investigates the seemingly unusual behavior of single crystal airfoil materials. The fatigue initiation processes in single crystal (SC) materials are significantly more complicated and involved than fatigue initiation and subsequent behavior of a (single) macrocrack in conventional, isotropic, materials. To understand these differences it is helpful to review the evolution of high temperature airfoils.

Characteristics of Single Crystal Materials

Modern gas turbine flight propulsion systems employ single crystal materials for turbine airfoil applications because of their superior performance in resisting creep, oxidation, and thermal mechanical fatigue (TMF). These properties have been achieved by composition and alloying, of course, but also by appropriate crystal orientation and associated anisotropy.

Early aeroengine turbine blade and vane materials were conventionally cast, equiaxed alloys, such as IN100 and Rene'80. This changed in the late 1960s with the introduction of directionally-solidified (DS) MAR-M200 + Hf airfoils. The DS process produces a <001> crystallographic orientation, which in superalloys exhibits excellent strain controlled fatigue resistance due to its low elastic modulus. The absence of transverse grain boundaries, a 60% reduction in longitudinal modulus compared with equiaxed grains, and its corresponding improved resistance to thermal fatigue and creep, permitted significant increases in allowable metal temperatures and blade stresses. Still further progress was achieved in the mid-1970s with the development of single crystal airfoils[1].

The first such material, PWA 1480, has a considerably simpler composition than preceding cast nickel blade alloys because, in the absence of grain boundaries, no grain boundary strengthening elements are required. Deleting these grain boundary strengtheners, which are also melting point depressants, increased the incipient melt temperature. This, in turn, allowed nearly complete γ' solutioning during heat treatment and thus a reduction in dendritic segregation. The absence of grain boundaries, the opportunity for full solution heat treatment, and the minimal post-heat treat dendritic segregation, result in significantly improved properties as compared with conventionally cast or directionally solidified alloys. Single crystal castings also share with DS alloys the <001> crystal orientation, along with the benefits of the resulting low modulus in the longitudinal direction.

Pratt & Whitney has developed numerous single crystal materials. Like most, PWA 1480 and PWA 1484 are γ' strengthened cast mono grain nickel superalloys based on the Ni-Cr-Al system. The bulk of the microstructure consists of approximately 60% by volume of cuboidal γ' precipitates in a γ matrix. The precipitate ranges from 0.35 to 0.5 microns and is an ordered Face Centered Cubic (FCC) nickel aluminide compound. The macrostructure of these materials

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[1] Gell, M., D. N. Duhl, and A. F. Giamei, 1980, "The Development of Single Crystal Superalloy Turbine Blades," *Superalloys* 1980, proceedings of the Fourth International Symposium on Superalloys, American Society for Metals, Metals Park, Ohio, pp. 205-214.

is characterized by parallel continuous primary dendrites spanning the casting without interruption in the direction of solidification. Secondary dendrite arms (perpendicular to solidification) define the interdendritic spacing. Solidification for both primary and secondary dendrite arms proceeds in <001> type crystallographic directions. Undissolved eutectic pools and associated microporosity reside throughout the interdendritic areas. These features act as microstuctural discontinuities, and often exert a controlling influence on the fatigue initiation behavior of the alloy. Also, since the eutectics are structurally dissimilar from the surrounding matrix their fracture characteristics will differ.

Single Crystal Fatigue

The fatigue process in single crystal airfoil materials is a remarkably complex and interesting process. In cast single crystal nickel alloys, two basic fracture modes, crystallographic and non-crystallographic, are seen in combination. They occur in varying proportions depending upon temperature and stress state. Crystallographic orientation with respect to applied load also affects the proportion of each and influences the specific crystallographic planes and slip directions involved. Mixed mode fracture is observed under monotonic as well as cyclic conditions.

Single crystal turbine blades are cast such that the radial axis of the component is essentially coincident with the <001> crystallographic direction which is the direction of solidification. Crystallographic fracture is usually seen as either octahedral along multiple (111) planes or under certain circumstances as (001) cleavage along cubic planes.

Non-crystallographic fracture is also observed. Low temperatures favor crystallographic fracture. At higher temperatures, in the 427C range, small amounts of non-crystallographic propagation have the appearance of transgranular fatigue in a related fine grain equiaxed alloy. Under some conditions, this propagation changes almost immediately to the highly crystallographic mode along (111) shear planes, frequently exhibiting prominent striations emanating from the fatigue origin and continuing to failure in overstress. Under other conditions the non-crystallographic behavior can continue until tensile failure occurs. At intermediate temperatures (around 760C) non-crystallographic propagation is more pronounced and may continue until tensile overload along (111) planes occurs, or may transition to subcritical crystallographic propagation. At 982C, propagation is almost entirely noncrystallographic, similar to transgranular propagation in a polycrystal.

Damage Catalogue

This program will identify and compile descriptions of the fracture morphologies observed in SC airfoil materials under various combinations of temperature and stress associated with advanced Navy aeropropulsion systems. We will suggest fatigue mechanisms for these morphologies and catalogue them as unique damage *states*. Most testing will be accomplished under ancillary funding, and therefore be available to this effort at not cost. The work is organized into four tasks, which are described in the following paragraphs.

II. Program Organization

The program is structured into four tasks, three technical and one reporting. The individual tasks are outlined here.

Task 100 - Micromechanical Characterization

This task will define the mechanisms of damage accumulation for the various types of fracture observed in single crystal alloys. These fracture characteristics will be used to establish a series of Damage States which represent the fatigue damage process. The basis for this investigation will be detailed fractographic assessment of failed laboratory specimens generated in concurrent programs. Emphasis will be on specifically identifying the micromechanical damage mechanisms, relating them to a damage state, and determining the conditions required to transition to an alternate state.

Task 200 - Analytical Parameter Development

This task will extend current methods of fatigue and fracture mechanics analysis to account for microstructural complexities inherent in single crystal alloys. This will be accomplished through the development of flexible correlative parameters which can be used to evaluate the crack growth characteristics of a particular damage state. The proposed analyses will consider the finite element and the hybrid Surface-Integral and Finite Element (SAFE) methods to describe the micromechanics of crack propagation.

Task 300 - Probabilistic Modeling

This task will model the accumulation of fatigue damage in single crystal alloys as a Markov process. The probabilities of damage progressing between the damage states defined in Task 100 will be evaluated for input into the Markov model. The relationship between these transition probabilities and fatigue life will then be exploited to establish a model with comprehensive life predictive capabilities.

Task 400 - Reporting

Running concurrently with the analytical portions of the program, this task will inform the Navy Program Manager and Contracting Officer of the technical and fiscal status of the program through R&D status reports.

III. Technical Progress

To date our progress reports have concentrated on micromechanics. This month's progress is discussed from the perspective of the Micromechanical Characterization (Task I) and from the standpoint of Probabilistic Modeling (Task III).

In previous reports we have discussed Initial Material Quality (IMQ) defect types found in PWA 1480 and HIP PWA 1484. The principal IMQ defect species (porosity, TaC and eutectics) have been quantified for comparative purposes via metallographic image analysis. Some of those results are included in this report; the remainder are being reduced and analyzed.

Micromechanics (Task I)

Once quantitative measurements of IMQ populations have been made it is necessary to consider the qualitative aspects of the various species of defects present. In our February report, FR2198-04, we discussed threshold size for the TaC vs. the eutectic phase. A review of available fractures has been conducted; based on that limited data base it appears that the threshold size is similar to the previously shown distribution for porosity. An example of one such initiation site is included in Figure 1, an initiation point from eutectic decohesion. A second example is shown in Figure 2; this defect's physical character resembles a micropore with its smooth interior contours. Upon decohesion a void with morphology similar to a pore develops. In contrast the TaC is a low ductility defect prone to brittle fracture initiating sharp microcracks in the bulk microstructure.

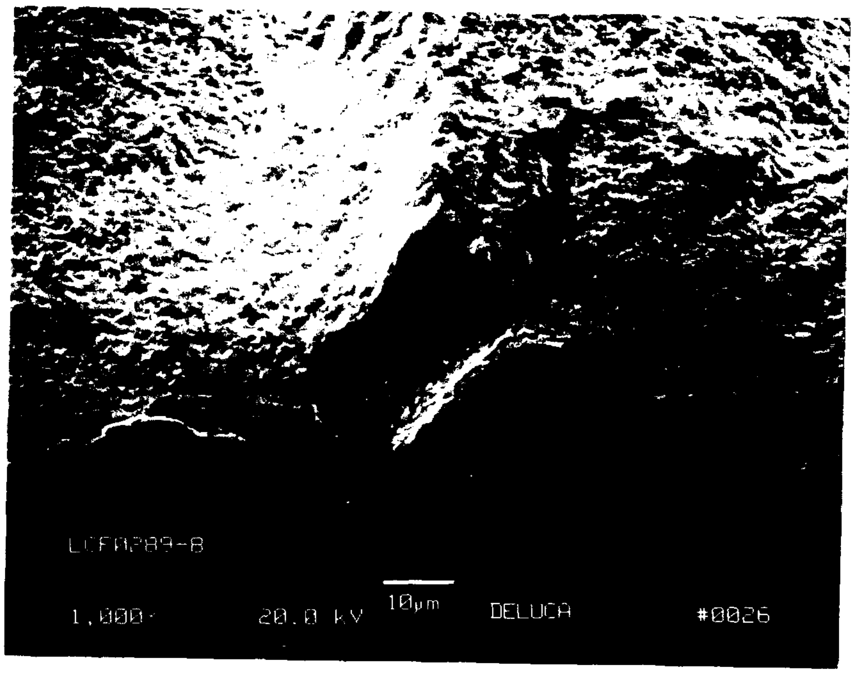


Figure 1: An Initiation Point From Eutectic Decohesion

Probabilistic Modeling (Task III)

The temperature dependency of the eutectic phase as a fatigue crack initiator complicates the approach to a probabilistic assessment of IMQ defects since the resulting statistical distribution may be influenced by the test condition. Ideally, IMQ would be Initial Material Quality and exist as a function of only the material chemistry and processing. Potential dependency on test conditions is under investigation.

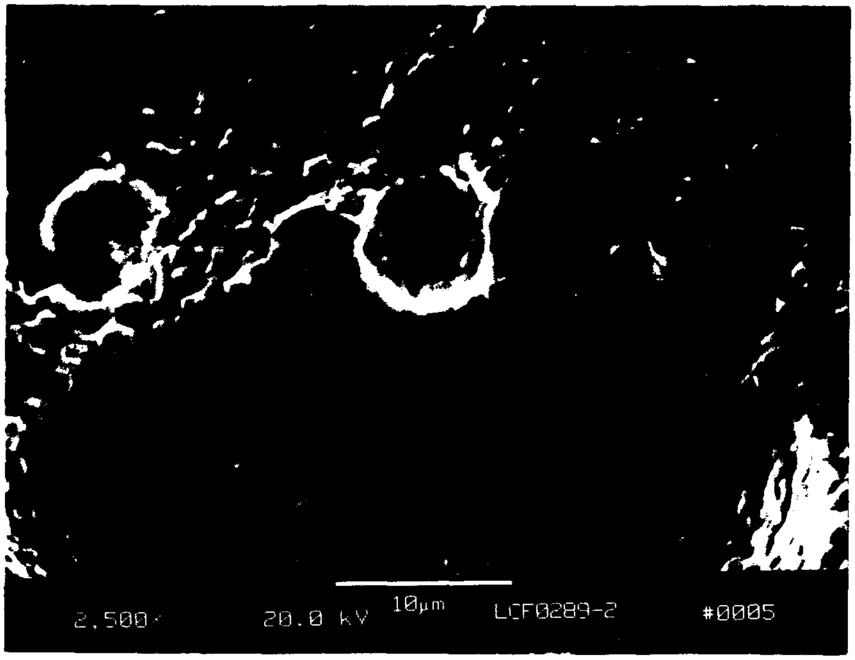


Figure 2: Defect Resembling a Micropore With Smooth Interior Contours

Also to be addressed is the relationship between distributions of IMQs obtained from metallographic and ex post facto fracture specimen analysis. Figure 3 shows a porosity distribution recently obtained via metallographic sectioning. In comparing this distribution to that obtained in February by archival specimen analysis, it appears that a model relating the two distributions could be developed. Should this be the case, metallographic sectioning results might be used to replace the extensive (and expensive) database required for archival specimen analysis.

Figure 4 compares the γ-γ' Eutectic distribution with the TaC distribution for Hiped PWA 1484.

There are insufficient archival specimen fractures available to define properly the activation temperature range for eutectic decohesion. A potential experimental method might be to conduct a constant K crack growth test with a controlled temperature gradient over time. Analysis of the fracture surface then would provide the temperature range where decohesion occurs. Examination of the relationship between the fracture surface and time/temperature might also provide additional microstructural information.

IV. Current Problems

No technical problems have been encountered during the reporting period.

Figure 3: Unetched PWA 1480 Porosity Distribution

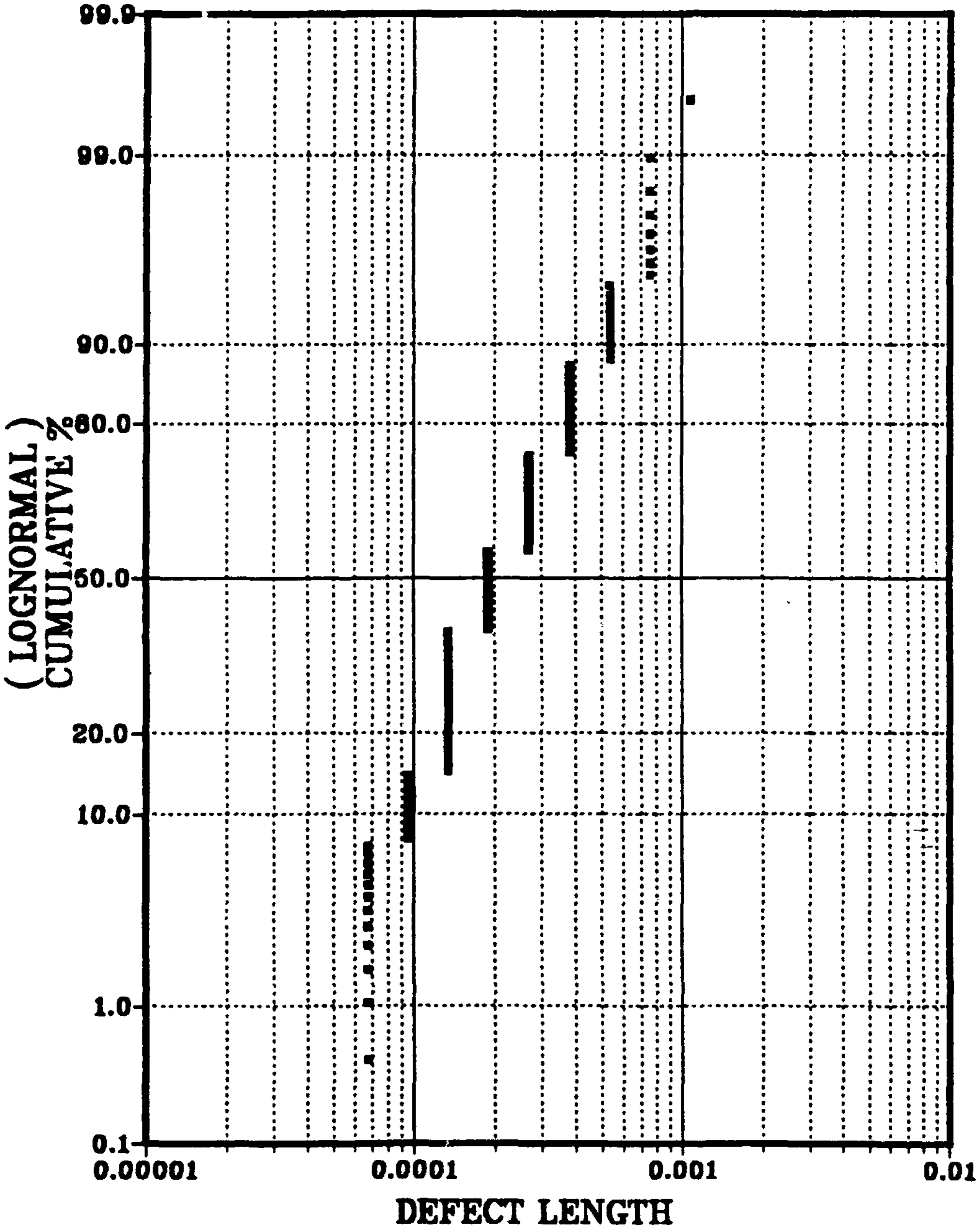
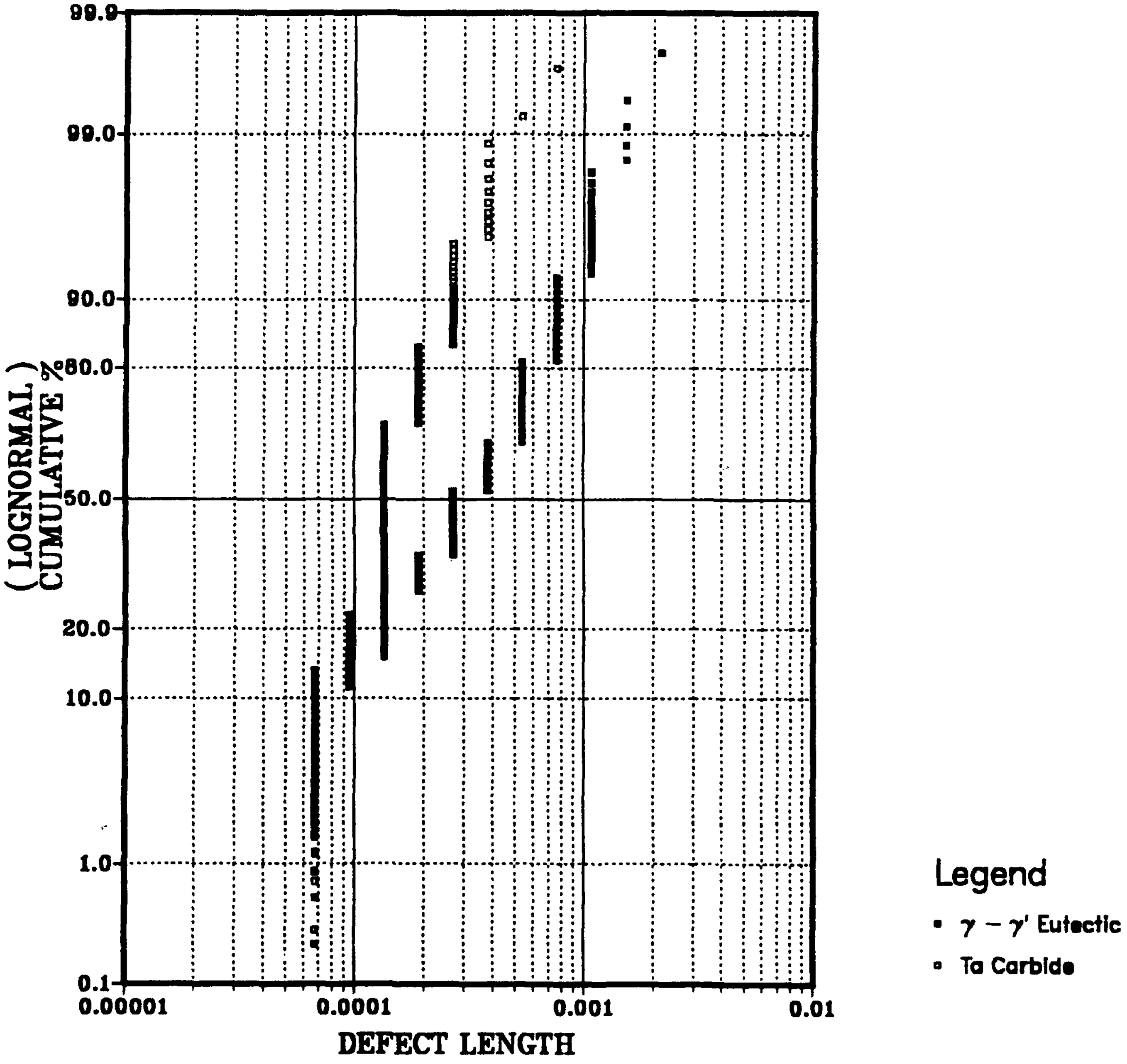


Figure 4: PWA 1484 + HIP $\gamma - \gamma'$ Eutectic vs. Tantalum Carbide Distributions



REPORT DOCUMENTATION PAGE	1. REPORT NO. FR2198-06	2.	3. Recipient's Accession No.

4. Title and Subtitle FATIGUE IN SINGLE CRYSTAL NICKEL SUPERALLOYS Technical Progress Report	5. Report Date 15 April, 1992
	6.
7. Author(s) Charles Annis	8. Performing Organization Rept. No. FR2198-06
9. Performing Organization Name and Address United Technologies Pratt & Whitney P. O. Box 109600 West Palm Beach, FL 33410-9600	10. Project/Task/Work Unit No.
	11. Contract(C) or Grant(G) No. (C) N00014-91-C-0124 (G)
12. Sponsoring Organization Name and Address Office of Naval Research Department of the Navy 800 N. Quincy Street Arlington, VA 22217-5000	13. Type of Report & Period Covered Interim 03/16/92 - 04/15/92
	14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

This program investigates the seemingly unusual behavior of single crystal airfoil materials. The fatigue initiation processes in single crystal (SC) materials are significantly more complicated and involved than fatigue initiation and subsequent behavior of a (single) macrocrack in conventional, isotropic, materials. To understand these differences is the major goal of this project.

17. Document Analysis a. Descriptors

Fatigue, Fracture, Single Crystal, PWA 1480, PWA 1484

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Unlimited	Unclassified	8
	20. Security Class (This Page)	22. Price

☆ GPO : 1993 O - 381-526 (8393)